Space Solar Power (SSP)
New Energy Options for the 21ST Century

Overview and Introduction

Space Solar Power Technical Interchange Meeting
GRC / OAI - Cleveland, OH

September 10-12, 2002

John C. Mankins
Chief Technologist, Human Exploration and Development of Space
Office of Space Flight
NASA Headquarters
Washington, D.C.

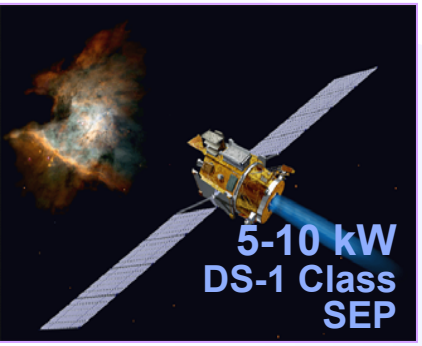
Space Solar Power Background
(1 of 2)

- **The Solar Power Satellite (SPS) concept was invented in 1968 by Dr. Peter Glaser and examined in the 1970s by DOE and NASA; however work stopped in 1980-1981 because ...**
  - The cost-to-first power > $250B ('96,$) for the 1979 SPS Reference System
  - Massive initial government investment in infrastructure required
  - Too many dramatic advances in technology needed
  - Largely a "US-only" proposition with poor international involvement
  - Reagan Administration (1980-1981) had other priorities
  - US OTA and NRC criticized early deployment (1990s) scenario strongly
  - Urgency faded as oil prices plummeted in the early 1980s
- **By the mid- to late- 1990's, this situation had changed substantially...**
  - A huge global market for new energy sources had developed
  - Concerns about "Greenhouse Gas" emissions and Global Climate Change emerged as a serious political/international issue
  - US National Space Policy assigned responsibility for NASA to drive ETO costs down dramatically (Independent of SPS/SSP) — and the "Space Launch Initiative (SLI) was initiated
  - Important technical advances had been made and new R&T avenues identified
  - Potential space applications of key technologies/systems had been identified – both for NASA and Commercial Space
  - Strong opportunities emerged, suggesting international interest and involvement

Space Solar Power Background
(2 of 2)

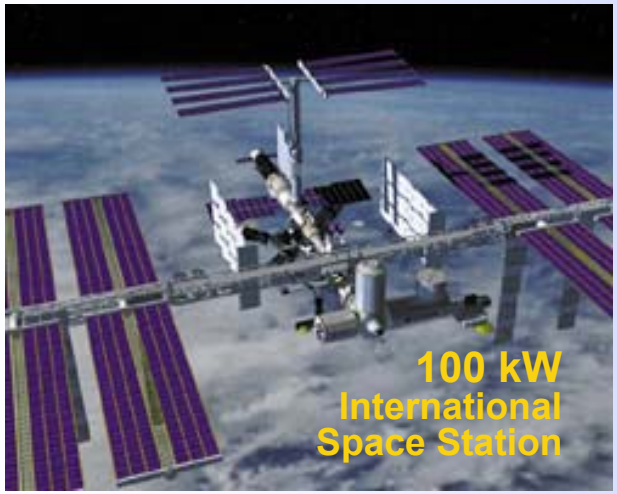
- **These changed resulted in part due to efforts within NASA**
  - During 1995-1997, NASA conducted a “Fresh Look” study of SSP concepts and technologies
    - Approaches emerged that appeared to be much more viable — technically and economically — than past systems designs
  - The US Congress / OMB expressed interest in SSP in Winter 1997/1998
    - A follow-on to the “Fresh Look” study was suggested
    - During 1998 NASA conducted a $2M SSP Concept Definition Study (CDS)
  - These efforts resulted in an initial SSP technology effort being undertaken
- **During FY 1999-2000, the “Space Solar Power (SSP) Exploratory Research and Technology (SERT) program was conducted (@~$22M)**
  - Including systems studies, technology research tasks, technology demonstrations
- **A key result of the SERT program was an independent peer review of NASA’s SSP R&T road maps, conducted by the US National Research Council**
- **During FY2001-FY2002, NASA is continuing SSP Concept and Technology Maturation (SCTM), with additional emphasis on**
  - System modeling tools
  - Critical technology research topics
  - Technology flight demonstrations

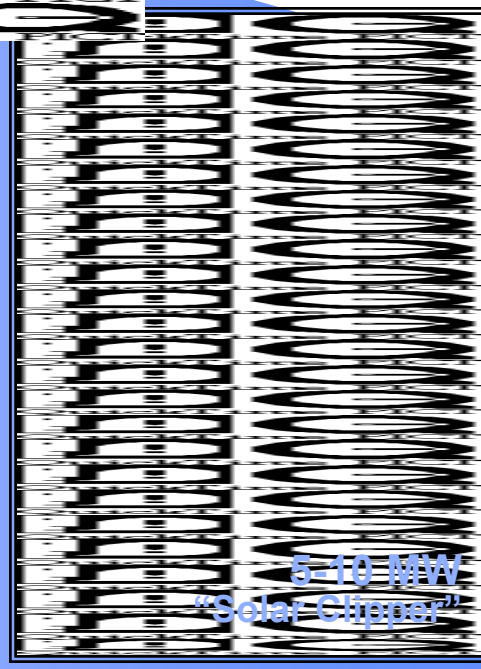
Space Power
Exploration and Commercial Development



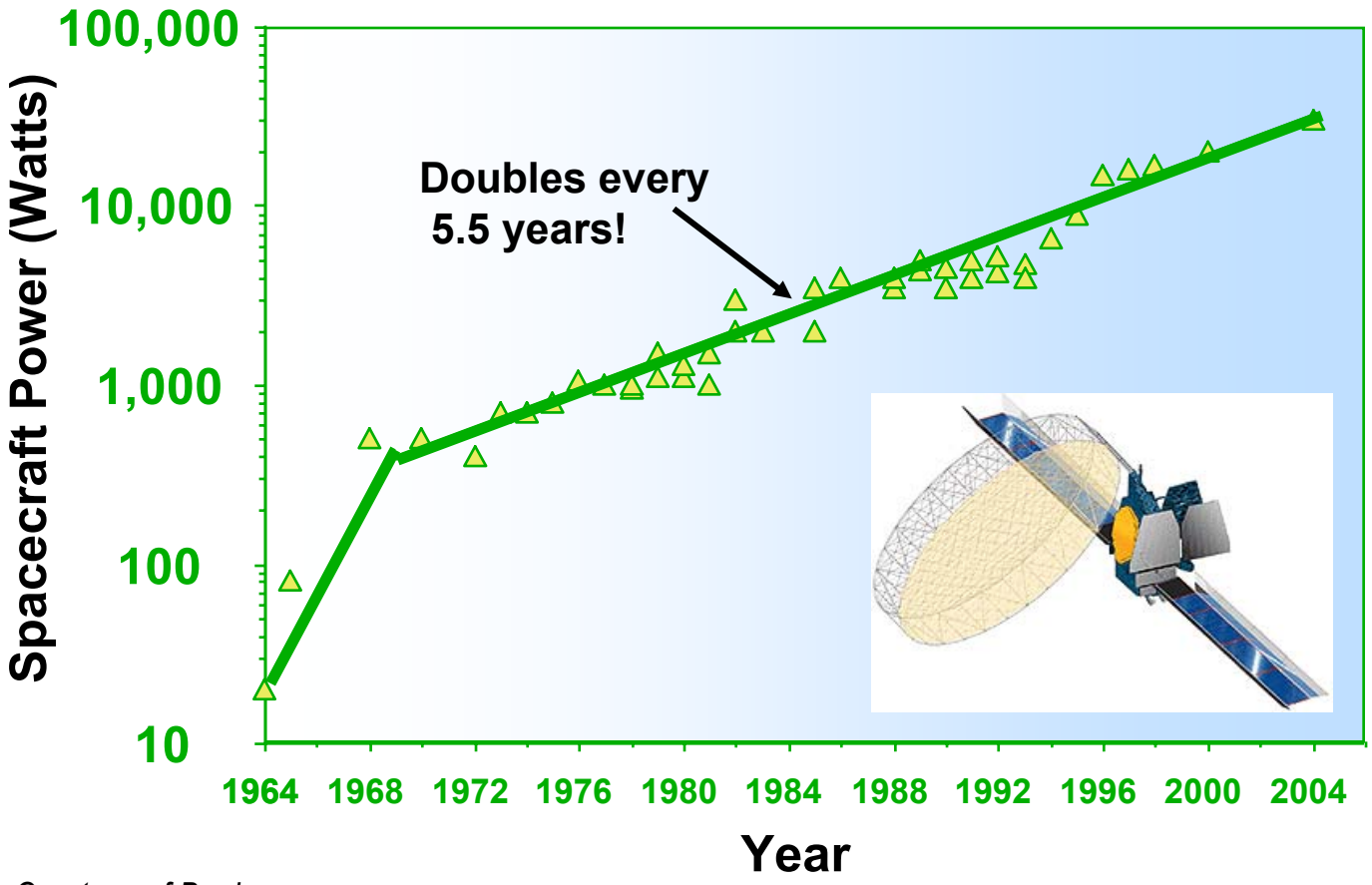
~ 25-50 kW
Hybrid
Propellant
Module

10 kW to 1 MW
Lunar Resources





Space Power
Communications / National Security Satellite Power Trends



Courtesy of Boeing

Future National Security Needs

SBR: on critical roadmap for >25kW power needs

SBL: Increased power identified as a top enabler

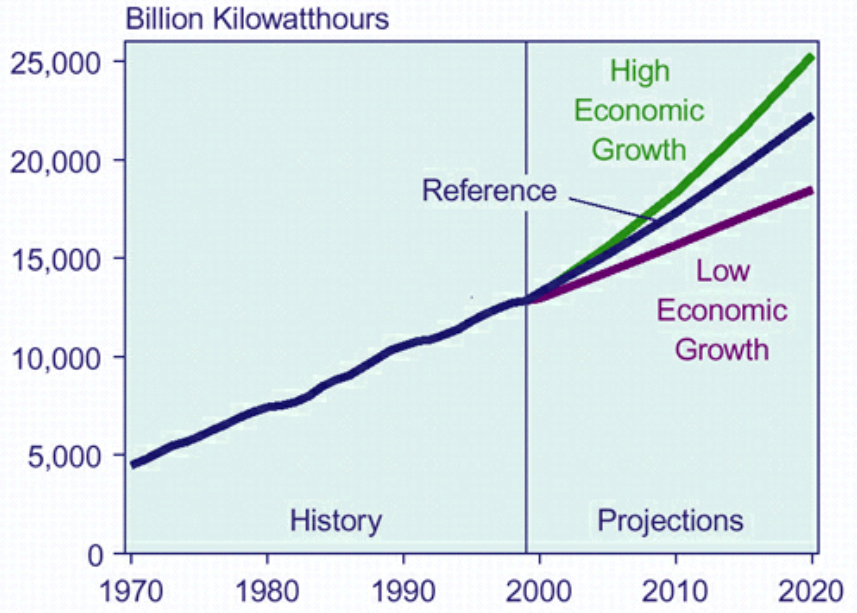
NRO: > 100kW

SMC/XR (Don Gasner): >100-200kW

Future Directions: Terrestrial Power
The Emerging Global Energy Marketplace

- **Global demand for energy is soaring due to growing populations and economies**
- **Electricity is the fastest growing end-use form of energy**
- **Organization for Economic Cooperation and Development (OECD) nations are the largest consumers of electricity**
- **Still, many are un-served or under-served**
  - 2 billion people not yet connected to electric power grids
- **NON-OECD nations will use more than 1/2 of the World's Energy by 2015**
- **However, there are serious environmental challenges**
  - Increasing emphasis is being place on renewable energy sources

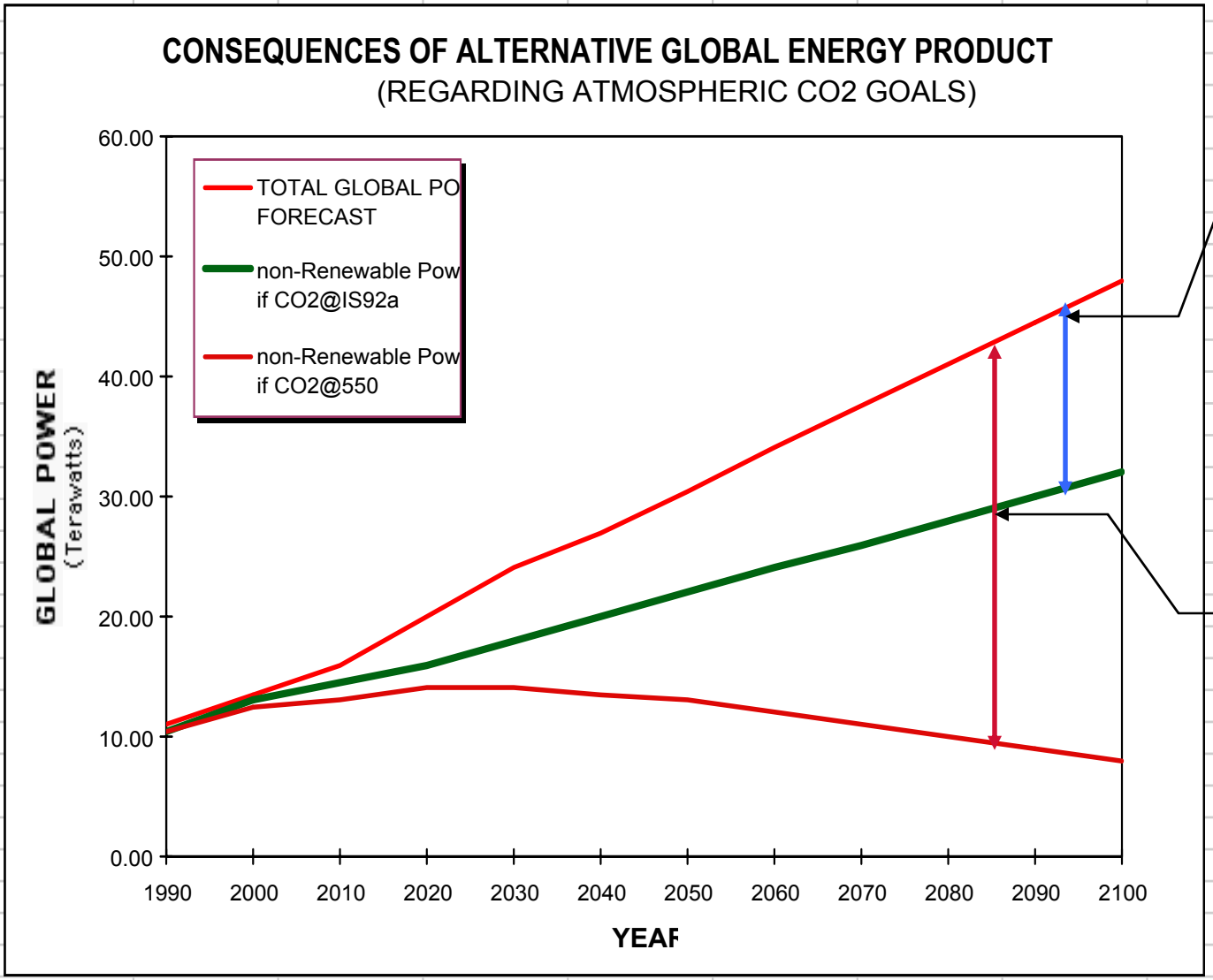
Figure 77. World Net Electricity Consumption in Three Cases, 1970-2020



Sources: **History:** Energy Information Administration (EIA), Office of Energy Markets and End Use, International Statistics Database and *International Energy Annual 1999*, DOE/EIA-0219(99) (Washington, DC, January 2001). **Projections:** EIA, World Energy Projection System (2001).

Where each 10 Billion Kilowatt-Hours is equivalent to 3 Million Tons of Coal

The Impact on Energy of Stabilizing CO_2 Levels in the Atmosphere



> 16 TW

Carbon-Neutral Power Generation Capacity Required to Stabilize the atmosphere at *4-times* pre-industrial CO2 levels

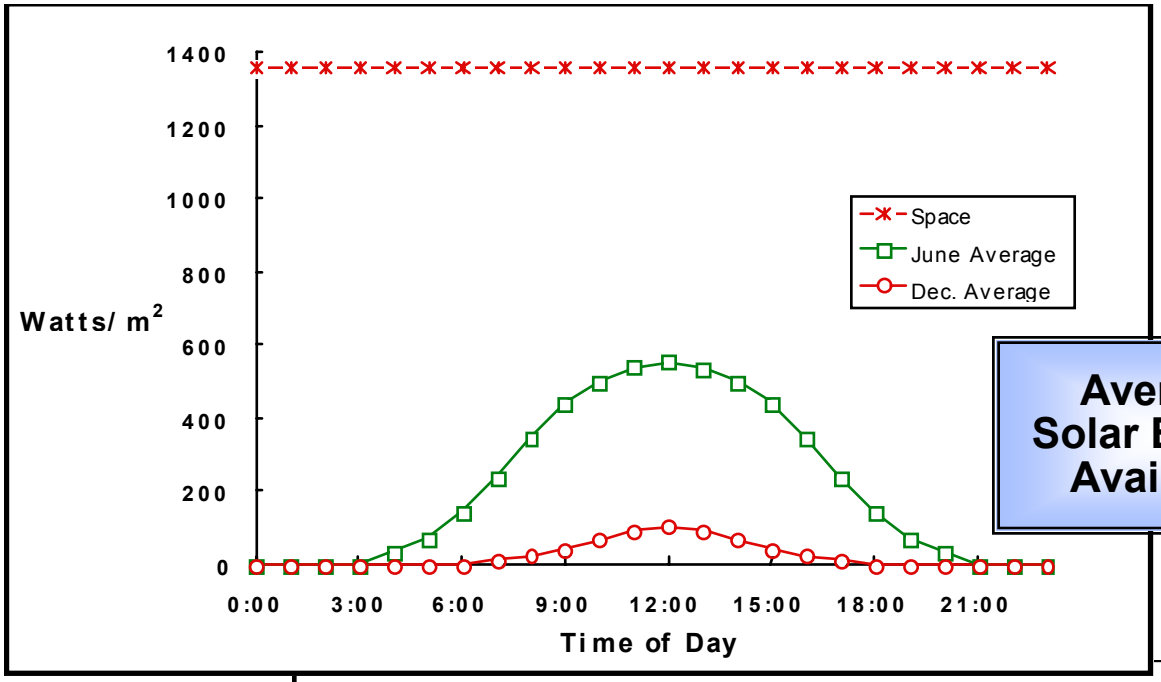
~ 40 TW

Carbon-Neutral Power Generation Capacity Required to Stabilize *at 2-times* pre-industrial levels

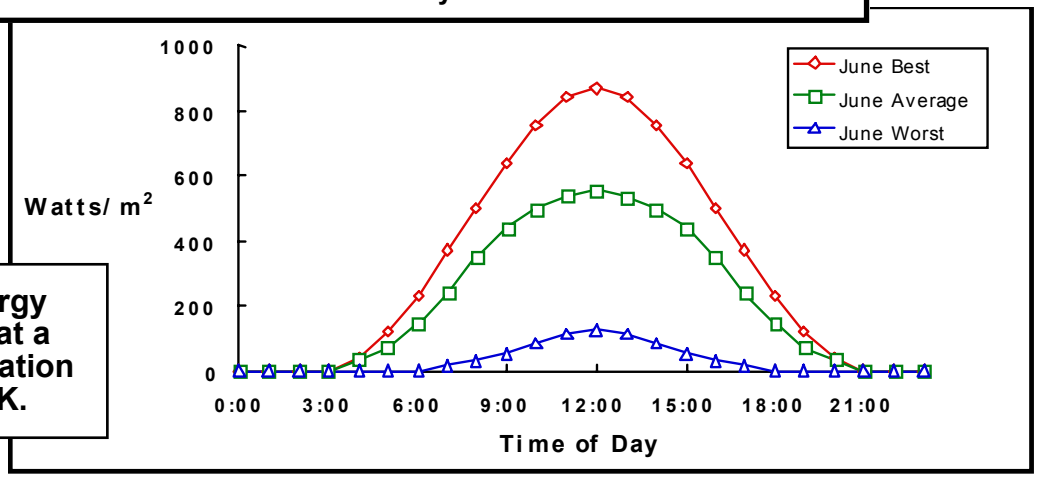
Comparison of Technology Challenges

Space Solar Power Compared to Terrestrial Solar Power

- **The technology challenge facing ground-based solar power systems is in many ways harder than that for space-based systems**
- **The total solar energy available at a typical site on the Earth's surface is much less than in space**
- **Moreover, the energy available varies widely — seasonally and daily – thus, requiring drastic over-capacity as well as costly large-scale energy storage to provide baseload power**

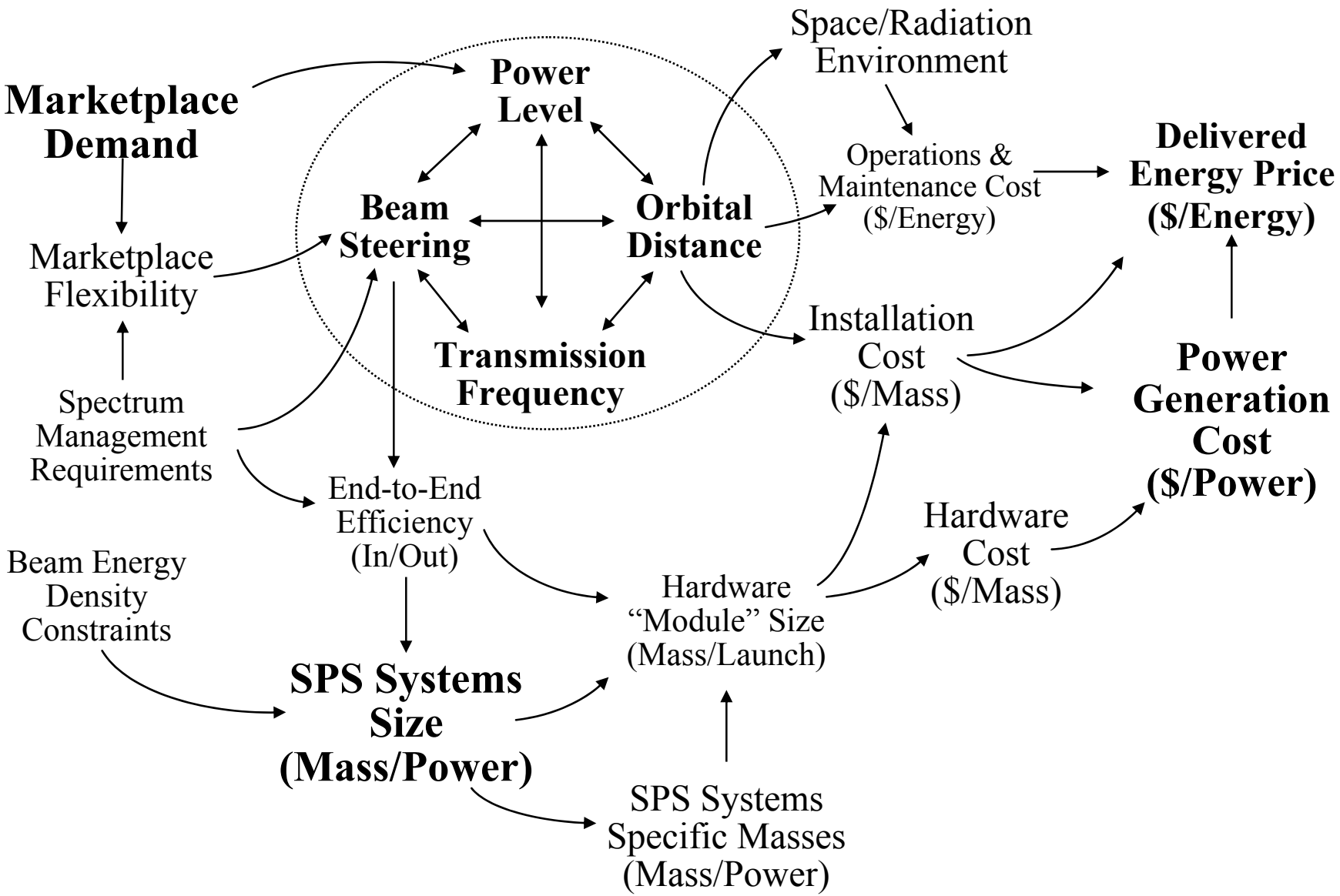


Average Solar Energy Available

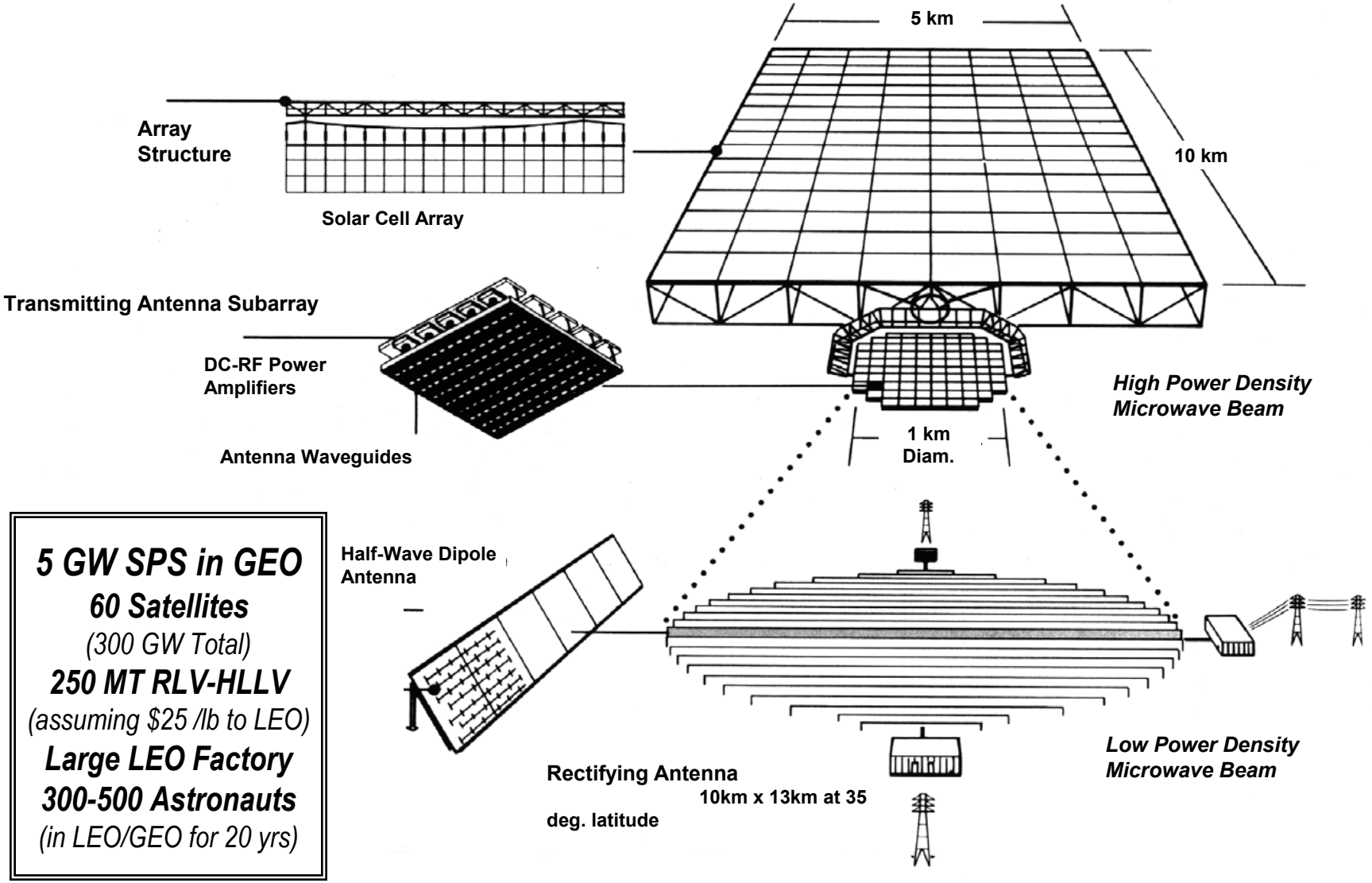


Solar Energy Available at a Typical Location in the U.K.

Challenge of Space Solar Power
Complex Network of SSP Concept Characteristics



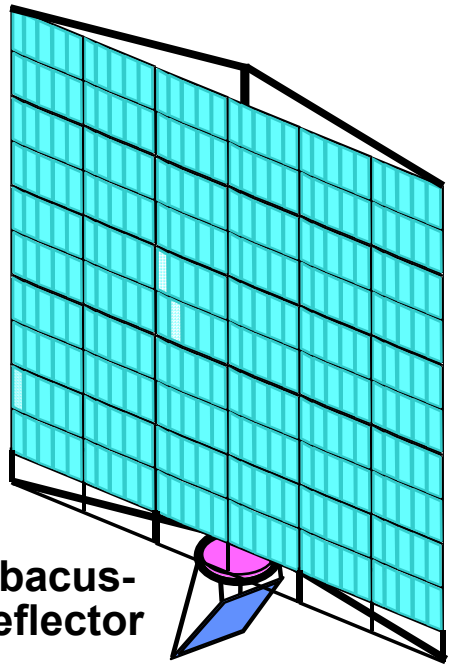
SOLAR POWER SATELLITES
1979 SPS Reference System Concept (GEO)

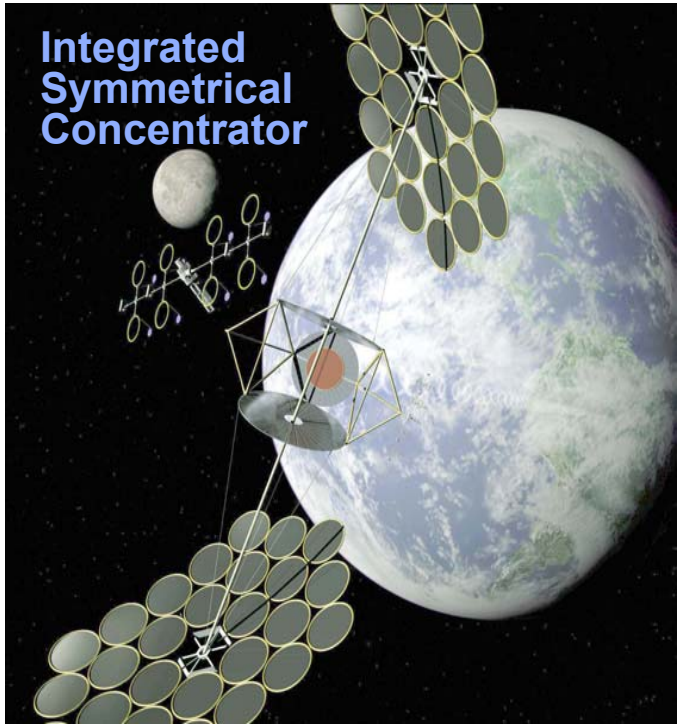


5 GW SPS in GEO
60 Satellites
(300 GW Total)
250 MT RLV-HLLV
(assuming $25 /lb to LEO)
Large LEO Factory
300-500 Astronauts
(in LEO/GEO for 20 yrs)

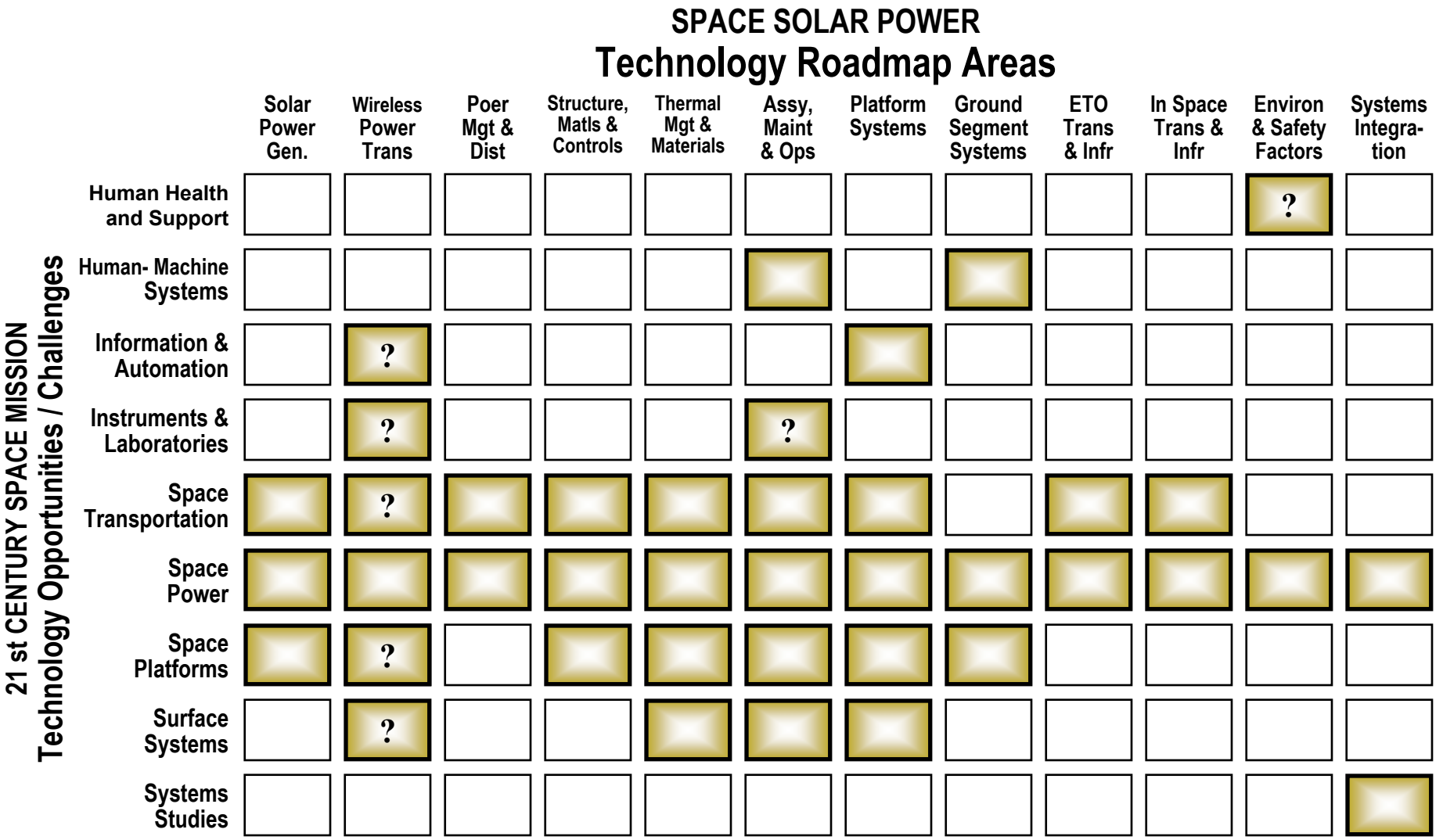
Recent SSP Concepts

- **A variety of space solar power satellite (SSPS) concepts have been examined during the past several years**
- **One goal in these studies as been to balance the need for a robust solution to the longer-term challenge of power from space for terrestrial markets with the nearer-term need to demonstrate SSPS**

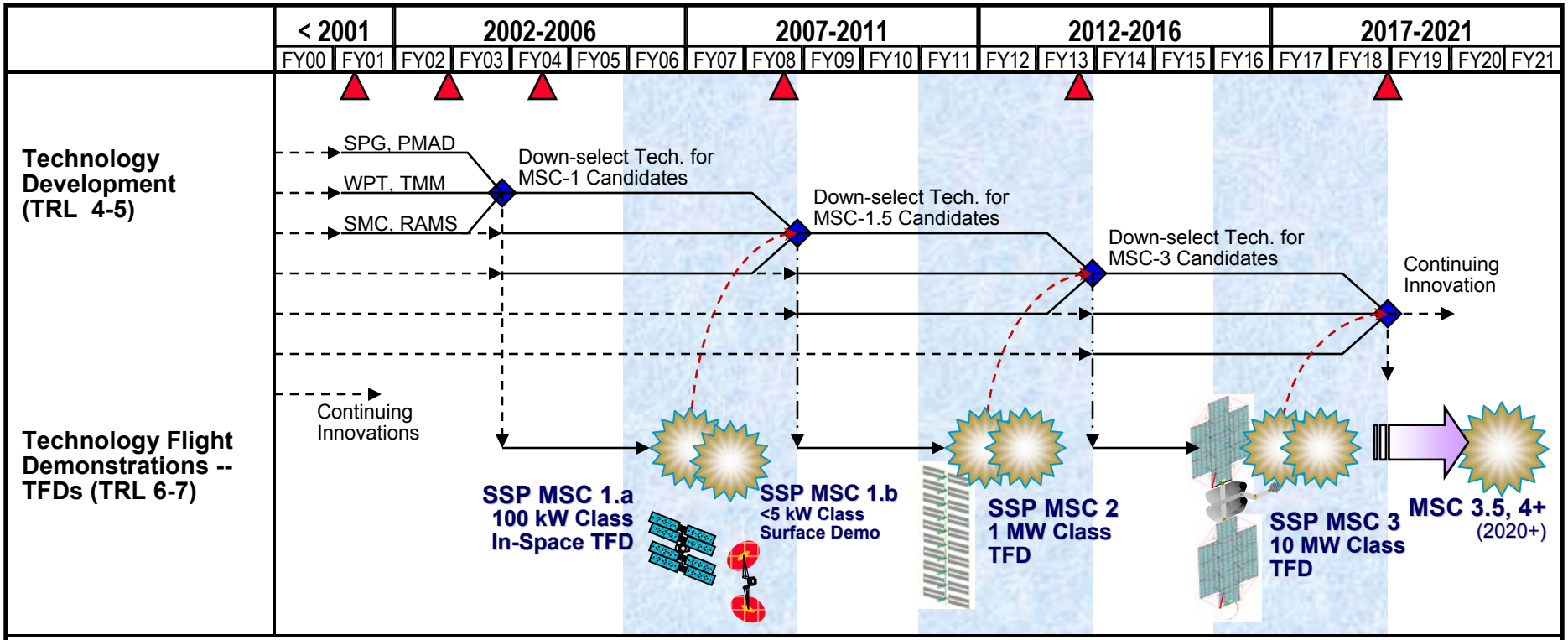




21st Century Space Mission Challenges and … SSP Technology Areas



Space Solar Power
Strategic Research & Technology Roadmap



Schedule of Milestones

▶	'99-'00	Complete initial Space Solar Power Exploratory Research and Technology (SERT) Program
	2001	Identify/refine top 2-3 systems concepts/architectures for each MSC Demonstration opportunity; refine interim applications
▶	2002/3	Establish/Integrate SSP test beds at participating organizations
	2003	Down-select technologies for initial 100kW class TFD
▶	2004/5	>200 W/kg Solar Power Generation (Array Level) in a Test Bed
		High-efficiency WPT (>10kW level) in a Test Bed
	2005	50 M class structures & controls flight experiments
	'06-'08	100KW Space-to-Ground & Space-to-Space SPG/WPT Demo
▶	2008	>400W/kg Solar Power Generation (Array Level in the Lab
		50 kW Solar Electric Propulsion/Generation Flight Test
		High-efficiency WPT (>100kW level) in a Test Bed
	2008	Down-select technologies for 1 MW class TFD
	'11-'13	1 MW Class Space to Space SPG/WPT Demo
▶	'12-'13	>600W/kg Solar Power Generation (Array Level)
	2013	Down-select technologies for initial 10MW class TFD
▶	2017	>1000W/kg Solar Power Generation (Array Level)
	'16-'18	10 MW CLASS INTEGRATED SSP SYSTEM FLIGHT DEMO

LEGEND ◆ Strategic Research and Technology Decision Point ▲ Major Technology Development Milestone ✸ Major Technology Flight Demonstration

Space Solar Power Background
Results of the US NRC SSP Review (1 of 2)

- **During 2000-2001, the Aeronautics and Space Engineering Board (ASEB) of the NRC assessed the technology investment strategy of the "Space Solar Power" Program to determine its technical soundness and contributed to the roadmap by…**
  - Critiquing the overall technology investment strategy in terms of the plan's likely effectiveness in meeting the program's technical and economic objectives
  - Identifying areas of highest technology investment necessary to create a competitive space-based electric power system
  - Identifying opportunities for increased synergy with other research and technology efforts
  - Providing an independent assessment of the adequacy of available resources for achieving the plan's technology milestones, and
  - Recommending changes in the technology investment strategy
- **Findings?**
  - "SERT program has provided a credible plan for making progress toward the goal of providing space solar power for commercially competitive terrestrial electric power despite rather large technical and economic challenges
  - "Current SSP technology is aimed at technical areas with important commercial, civil, and military application
  - "Dedicated NASA team has defined a potentially valuable future program…
  - "Current SSP program is operating on minimal budget and significantly higher funding and program stability will be necessary to attain aggressive goals of program
  - "Funding plans during the first five years (leading to first flight test demonstration) are reasonable…"

Space Solar Power Background
Results of the US NRC SSP Review (2 of 2)

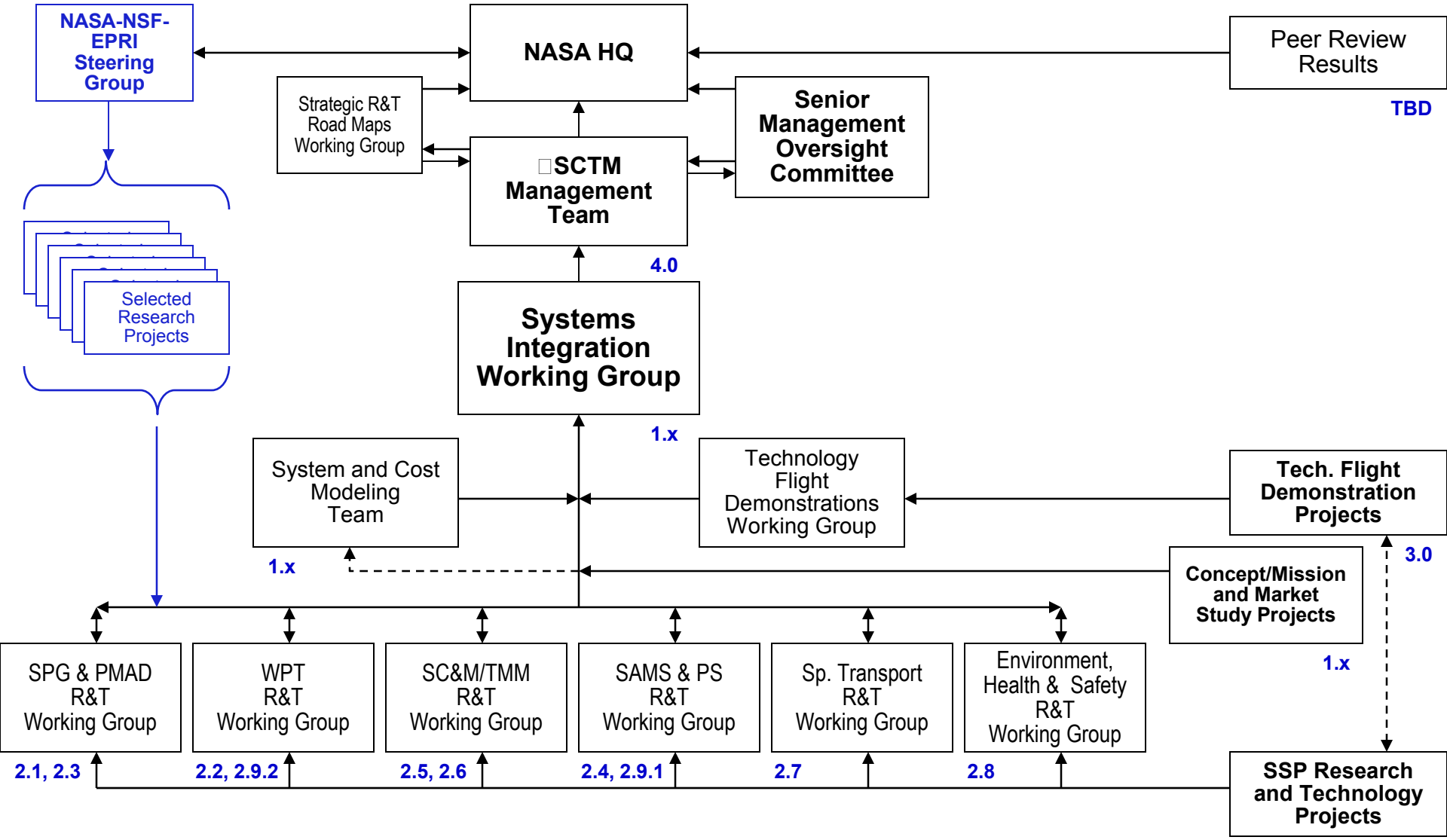
- **Findings? (continued)**
  - "Concern in committee that investment strategy is based on modeling efforts and individual mass, cost, and performance goals that may guide management toward poor investment decisions
  - "Significant technical breakthroughs necessary to achieve final goal of cost-competitive terrestrial baseload power
  - "Ultimate success of terrestrial power application critically depends on dramatic reductions in cost of transportation from Earth to GEO
  - "Leveraging of technological advances made by organizations external to NASA must be done."
- **The SSP R&T panel also made a series of recommendations for improving the management and focus of future program efforts, including**
  - Need to prepare a formal technology plan
  - Need for improvements in systems and cost modeling, including increased use of expert critique and review
  - Continued use of technology flight demonstrations
  - Early emphasis on environmental, health and safety issues
  - Key technologies:
    - Solar Power Generation
    - Wireless Power Transmission
    - Space Power Management and Distribution
    - Assembly, Maintenance and Serving
    - In-Space Transportation

Approach

- **NASA's SCTM Program is being conducted by a broadly-based, well-balanced team**
  - Implemented over approximately 12+ months, with continuing research tasks as funded from FY 2002 funds
  - A National Team, spanning several NASA centers, other Agencies, National Labs, US industry and universities
  - With technical and management reviews by Independent non-NASA experts in energy, aerospace technology, etc., to examine SSP concepts, options, risks, and provide inputs for future planning
  - Including coordination with International organizations, as appropriate
  - With both "In-house" and competitively procured activities
- **The SCTM is pursuing a focused portfolio of investments, guided by systems studies with the maximum degree of leveraging of existing resources inside and outside NASA; comprised of 3 complementary elements:**
  - Systems Studies and Analysis: new concept definition studies; analysis of systems and architecture concepts (including space applications); high-level modeling; detailed modeling of select concept; and potential terrestrial and space market economic analyses
  - Enabling Research & Technology: tightly focused exploratory research targeting longer-term "tall poles" and analysis to identify/establish technical viability to "first-order" for promising concepts
  - Technology Demonstrations: Initial, small-scale demonstrations of selected SSP concepts and/or components using nearer-term technologies, with an emphasis on enabling multi-purpose (space or terrestrial) applications of SSP and related systems/technologies; and small- to large- scale demonstrations of SSP concepts/components/systems using mid- to far-term technologies, with an emphasis on enabling multi-purpose (space or terrestrial) applications of SSP and related systems or technologies

SSP Concept & Technology Maturation (SCTM) Program

Program Integration



Inter-Agency Partnerships

- **To strengthen and broaden our investments in Space Solar Power (SSP) research and technology (R&T), NASA has worked with the National Science Foundation (NSF) to develop an important new inter-Agency partnership**
  - Partners include: NASA, the NSF and the Electric Power Research Institute (EPRI)
- **All three organizations are jointly sponsoring a broad area announcement -- to be release shortly -- to pursue critical, high-leverage SSP R&T challenge areas**
  - For information: Search on "JIETSSP" at www.nsf.gov
- **Minimum Commitment for FY2002 Round: $3.1M**
  - $1.5M from NASA's FY 2002 SSP funding
  - $1.5 M from NSF (4 Research Divisions)
  - $0.1M from EPRI
- ***This is the first inter-Agency funding related to SSP/SPS since the joint DOE-NASA studies of the 1970s…***

Summary of 2002 Activities
Space Solar Power Partnership with NSF

- **New Projects selected on July 12, 2002, for funding by collaborative NASA-NSF-EPRI SSP program**
  - Intelligent Cooperative Robots (PI: Si, Arizona State)
  - Coordination of Robotic Teams (PI: Singh, Carnegie Mellon University)
  - Comnet delays and controlled networked robots (PI: Abdalla, U. New Mexico)
  - Assembly systems via self Re-configurable Robots (PI: Shen, USC)
  - Intelligent diagnostics and operation of power grid (PI: Johnson, Howard University)
  - Advanced (Quantum Structure) Solar Cells (PI: Rafaelle, Rochester Institute of Tech.)
  - Microwave Power Beaming (PI: Pavlidis, University of Michigan)
  - Microwave Power Beaming (PI: Little, Texas A&M)
  - Power Converter Design (PI: Enjeti, Texas A&M)
  - Concentrator (Multi-Bandgap) Solar Cells (PI: O'Neil, ENTECH)
  - Microchannel Cooling Technology (PI: Henderson,, U. of Cincinnati)
  - Comprehensive Economics/Environmental Analysis (PI: Macauley, RFF)
- **Total scope: ~ $3M**

International SSP and Related Activities

- **Japan**
  - Phase A Study by USEF, sponsored by METI to define an initial SPS Technology Flight Demo
  - Various studies/technology research and development by NASDA
  - Professional Societies, etc.
- **Canada/CSA**
  - "Canadian Space Power Initiative" (modestly funded Study activities)
- **Europe / European Space Agency**
  - General Studies Programme (GSP) relating to Space Exploration and Utilization (SEU)
  - France/CNES
    - La Reunion Island wireless power transmission (WPT) demonstration program; SSP-related studies
  - Germany
    - SSP/HEDS-Type System and Infrastructure Modeling (H. Koelle)
- **International Astronautical Federation / IAA**
  - Power Committee Annual Symposia and Workshops, including upcoming World Space Congress
  - IAA Commission III study group addressing future exploration and development of space
- **Russia**
  - RF WPT investigations – at Keldysh; related research and technology (R&T) – at Moscow State University; SSP-related applications studies (e.g., ISTC 1172, 2120) – led by Keldysh, at various locations; various studies – through the Russian Academy of Sciences
- **United Nations**
  - UNISPACE-III workshop on solar power from space
  - International Telecommunications Union (ITU) / WP1A
  - UNESCO / World Solar Program
  - Potential sponsor of 2002 SSP International Forum

Japan and The United States are Global Leaders in Space Solar Power

How Much Is Energy Research & Development Worth As Insurance?

Annual Reviews: Energy and the Environment (1999. 24:487-512)

In this paper, we estimate the value of energy technology research and development (R&D) as an insurance investment to reduce four risks to the United States. These four risks are (a) the costs of climate stabilization, (b) oil price shocks and cartel pricing, (c) urban air pollution, and (d) other energy disruptions. The total value is estimated conservatively to be **>$12 billion/year**. However, only about half of this total may be warranted because some R&D is applicable to more than one risk. Nevertheless, the total Department of Energy investment in energy technology R&D [~$1.5 billion/year in fiscal year 1999 (FY99)] seems easily justified by its insurance value alone. In fact, a larger investment might be justified, particularly in the areas related to climate change, oil price shock, and urban air pollution. This conclusion appears robust even if the private sector is assumed to be investing a comparable amount relevant to these risks. No additional benefit is credited for the value to the economy and to the competitiveness of the U.S. from better energy technologies that may result from the R&D; only the insurance value for reducing the potential cost of these four risks to society was estimated.

Authors:

Robert N. Schock[1], William Fulkerson[2], Merwin L. Brown[3], Robert L. San Martin[4], David L. Greene[5], and Jae Edmonds[6]

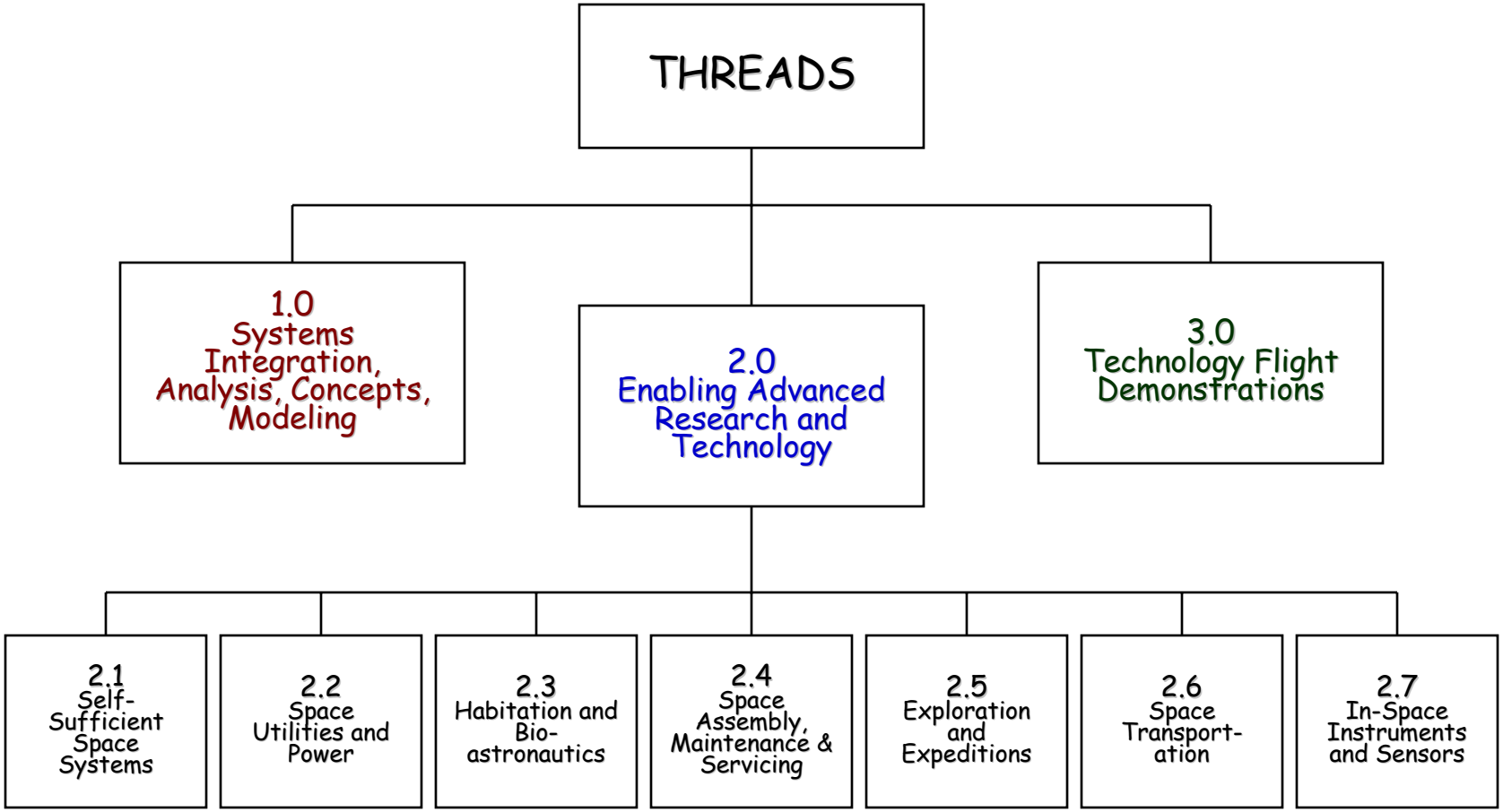
1 Lawrence Livermore National Laboratory/University of California, Livermore, California 94550;
2 Joint Institute for Energy and Environment, University of Tennessee, Oak Ridge National Laboratory and Tennessee Valley Authority, Knoxville, Tennessee 37996-4138;
3 Pacific Northwest National Laboratory, Richland, Washington 99352;
4 U.S. Department of Energy, Washington, DC 20585;
5 Oak Ridge National Laboratory, Oak Ridge Tennessee 37831-6073;
6 Pacific Northwest National Laboratory, Washington, DC 20024

KEY WORDS: climate change, oil price shock, urban air pollution, energy disruptions

Summary

- **Needed progress is being made in the area of Space Solar Power**
  - The new inter-Agency partnership among NASA, NSF and EPRI should substantially broaden and strengthen SSP R&T effort
- **Selected objectives for FY 2002 include:**
  - Challenge-focused in-house R&T efforts
  - Competitively-selected high-leverage out-of-house R&T projects (through the inter-Agency partnership)
  - Better definition of potential technology flight demonstrations
  - Examination of potential interim applications and deployments of SSP, including Earth-Neighborhood systems, power relay satellites, and others…
- **A number of international activities are ongoing**
  - Particularly in Japan (SSP technology flight demonstration studies), and in Russia (SSP technologies applied to interplanetary human exploration missions)
- **The SSP program is planning a major presence at the upcoming World Space Congress (Houston, October 2002)**
- **The various technologies of SSP are Integral to the Agency's "THREADS" Strategic R&T Road Maps**
- **This Technical Interchange Meeting is an important step in the advancement of Space Solar Power…**

THREADS UPDATE - 2002
Work Breakdown Structure



FY 2002 Revision

SSP Technical Interchange Meeting Goals and Objectives

- **The purposes and anticipated outcomes of the TIM are the following:**
  - Report status of current tasks from all participating NASA centers, academic institutions, industry and other government agencies.
  - Provide a forum for exchange of information on latest programmatic developments affecting the future activities of SSP.
  - Hold workshops on SSP technical and programmatic areas to develop concepts, discuss issues, and possible solutions. Review existing SSP technical area roadmaps and revise per latest developments
  - Discuss SSP systems integration issues.
  - Hold discussion on potential technologies for flight demonstrations, which are key to the challenge of SSP

Back Up Charts

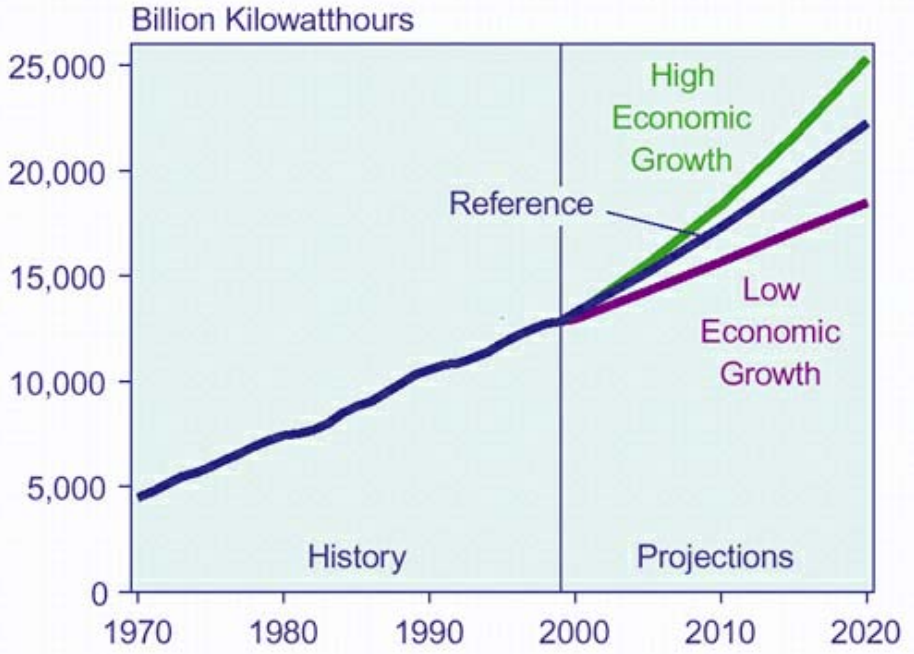
NSF-NASA Joint Workshop

- **In April 2000, during the SERT Program, NASA and the National Science Foundation (NSF) co-sponsored a workshop on revolutionary robotics and SSP**
- **Goal: Identify major cost uncertainties and possibilities for cost reduction through high-risk R&D**
- **The workshop explored the potential for future NSF-supported work related to**
  - Rational risk-management planning of R&D
  - Computational intelligence for robotics
  - Microwave technology
  - Power grid management and devices

- **Results can be found at:**

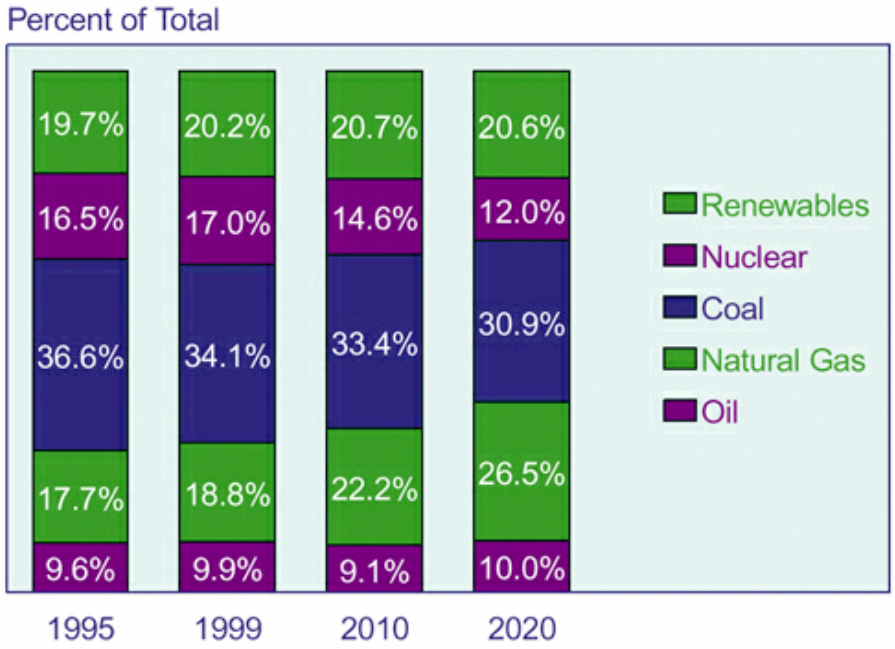
  robotics.use.edu/workshops/ssp2000/index.html

Figure 77. World Net Electricity Consumption in Three Cases, 1970-2020



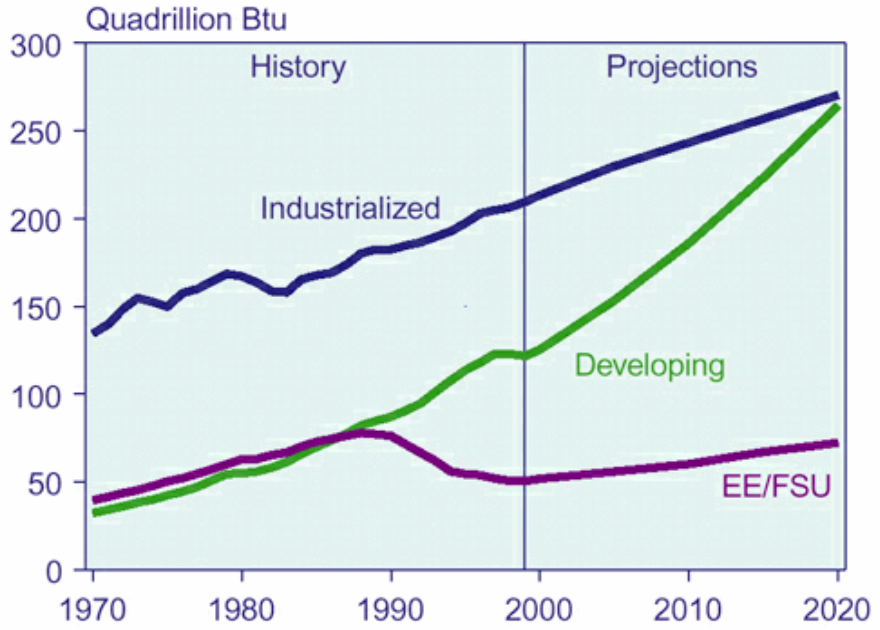
Sources: **History:** Energy Information Administration (EIA), Office of Energy Markets and End Use, International Statistics Database and *International Energy Annual 1999*, DOE/EIA-0219(99) (Washington, DC, January 2001). **Projections:** EIA, World Energy Projection System (2001).

Figure 78. Fuel Shares of Energy Use for Electricity Generation, 1995, 1999, 2010, and 2020



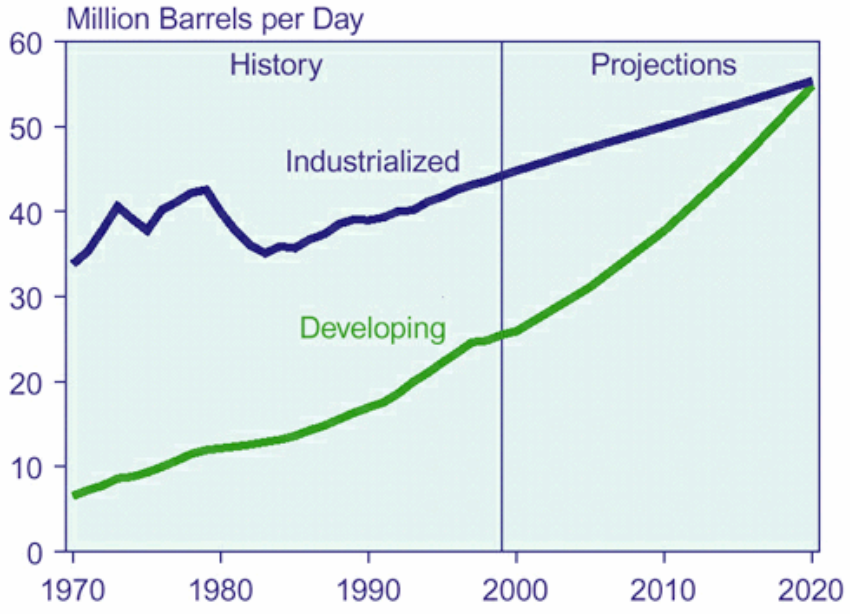
Sources: **1995 and 1999:** Energy Information Administration (EIA), *International Energy Annual 1999*, DOE/EIA-0219(99) (Washington, DC, January 2001). **2010 and 2020:** EIA, World Energy Projection System (2001).

Figure 3. World Energy Consumption by Region, 1970-2020



Sources: **History:** Energy Information Administration (EIA), Office of Energy Markets and End Use, International Statistics Database and *International Energy Annual 1999*, DOE/EIA-0219(99) (Washington, DC, January 2001). **Projections:** EIA, World Energy Projection System (2001).

Figure 7. Oil Consumption in the Industrialized and Developing Regions, 1970-2020



Sources: **History:** Energy Information Administration (EIA), Office of Energy Markets and End Use, International Statistics Database and *International Energy Annual 1999*, DOE/EIA-0219(99) (Washington, DC, January 2001). **Projections:** EIA, World Energy Projection System (2001).

Potential Issues
SPS / WPT Requirements for Restricted Airspace

Point of Comparison: Nuclear Power Plants (post 9-11)

Atomic Energy Commission wants no-fly zones over Indian plants

- NEW DELHI - India's Atomic Energy Commission (AEC) has asked the Ministry of Civil Aviation to declare air corridors over its nuclear installations "no-fly" zones.
- AEC authorities are reviewing the security situation around these centers after the FBI issued an international alert about possible attacks by Islamic terrorists. India and Pakistan have agreed upon not to attack each other's nuclear installations, but sources told Indian media they fear a strike by "non-state" groups, such as terrorists.
- Indian officials said Feb. 5 they plan to use low-level radars to detect air intrusion into Indian borders.
- "The Indian air force is tasked to scramble and shoot down any incoming alien aircraft. However, reaction time would be more if the entire area is declared a no-fly zone. Then any flying object would be easily identifiable as a friend or a foe," a source said.
- The Indian navy and coast guard have placed additional high-speed interceptor boats off the coast of Mumbai to protect the Bhaba Atomic Research Center. Anti-aircraft guns also have been deployed for that purpose.
- "Requests for additional anti-aircraft guns [have] also come in," a source said. "This is to protect [the] Narora atomic power plant, [the] Rajasthan atomic power station in Karnataka, [the] Indira Gandhi Center for Atomic Research and [the] Madras atomic power station in Tamil Nadu."

Aerospace Daily (7 February 2002; Article:198607; Copyright 2002 The McGraw-Hill Companies, Inc. (Joshua Newton))

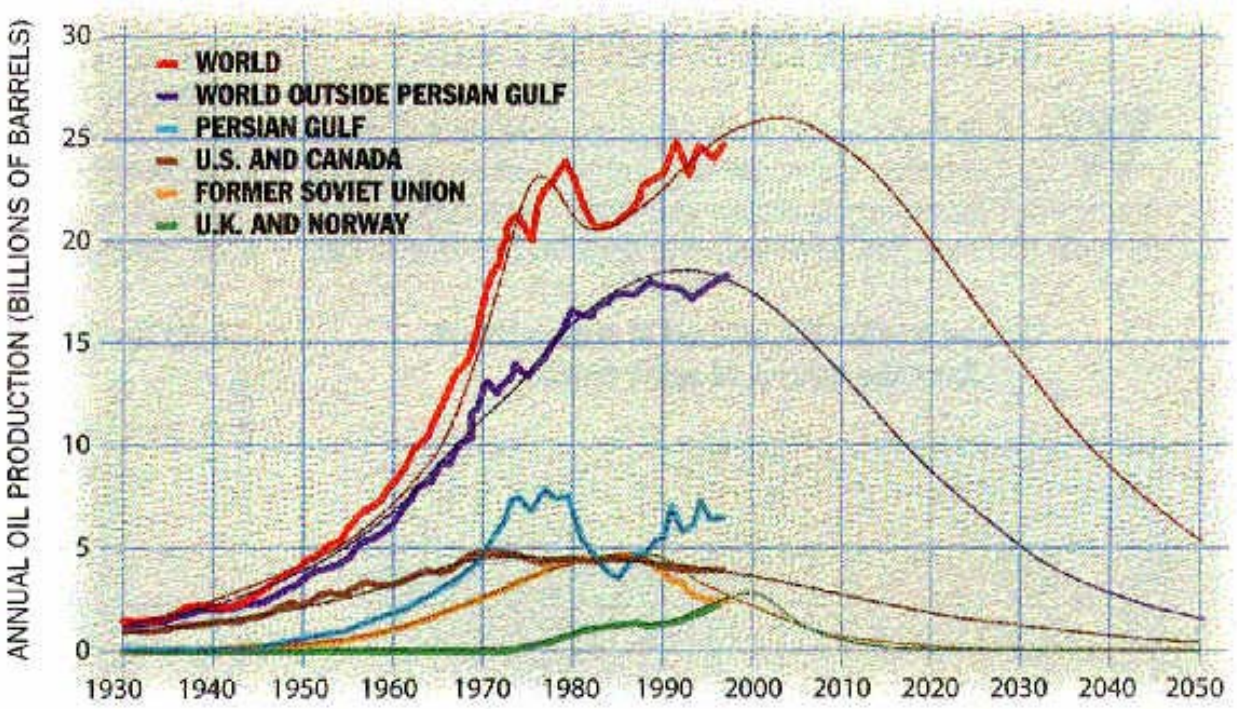
Potential Issues
"Permanently Low" Fossil Fuel Prices?

There is no consensus view concerning the future of fossil fuels

- ***<u>However</u>*, an increasing number of geologists are predicting that during the next 10-20 years, global oil production will fall behind global oil demand**

Similar forecasts have been made for natural gas

- **The likely result, given continuing increases in demand, could be sharp increases in the price of fossil fuels**



PREDICTED PEAK IN WORLD OIL PRODUCTION

SOURCE	PEAK DATE
F. Bernabe, ENI SpA (1998)	2000-2005
C. Campbell and J. Laherrére, Petroconsultants (1998)	2000-2010
J. MacKenzie, World Resources Institute (1996)	2007-2014
OECD's International Energy Agency (1998)	2010-2020
J. Edwards, University of Colorado, Boulder (1997)	~2020
DoE's Energy Information Administration (1998)	>2020
W. Fisher; U of Texas, Austin (1998)	2030-2040

Reference: Scientific American (March 1998); by Colin J. Campbell and Jean H. Laherrère

How Much Is Energy Research & Development Worth As Insurance?